ENVIRONMENTAL HEALTH PERSPECTIVES

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http://dx.doi.org/10.1289/EHP194

Received: 21 April 2015
Revised: 7 December 2015
Accepted: 7 June 2016
Published: 29 July 2016

Environ Health Perspect DOI: 10.1289/EHP194
Advance Publication: Not Copyedited

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Short running title: Mortality due to vegetation-fire $PM_{2.5}$ in Europe

Acknowledgements: The research has received funding from the Finnish Funding Agency for Technology and Innovation (TEKES, grant agreements 40207/08 and 40394/10), from the Academy of Finland (grant agreements 267675 and 122870), and from the European Union 7th Framework Programme for the research project "Transport Related Air Pollution and Health impacts - Integrated Methodologies for Assessing Particulate Matter" (TRANSPHORM, grant agreement 243406).

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Competing financial interests declaration

The authors declare they have no actual or potential competing financial interests.

Abstract

Background: Vegetation fires can release substantial quantities of fine particles ($PM_{2.5}$), which are harmful to health. The fire smoke may be transported over long distances and can cause adverse health effects over wide areas.

Objective: We aimed to assess annual mortality attributable to short-term exposures to vegetation-fire originated $PM_{2.5}$ in different regions of Europe.

Methods: $PM_{2.5}$ emissions from vegetation fires in Europe in 2005 and 2008 were evaluated based on the MODIS satellite data on fire radiative power. Atmospheric transport of the emissions was modelled using the chemical transport model SILAM. Mortality impacts were estimated for 27 European countries based on (i) modelled daily $PM_{2.5}$ concentrations and (ii) population data, both presented in a 50×50 km^2 spatial grid, (iii) an exposure-response function for short-term $PM_{2.5}$ exposure and daily non-accidental mortality, and (iv) country-level data for background mortality risk.

Results: In the 27 countries overall, an estimated 1483 and 1080 premature deaths were attributable to the vegetation-fire originated $PM_{2.5}$ in 2005 and 2008, respectively. Estimated impacts were highest in southern and eastern Europe. However, all countries were affected by fire-originated $PM_{2.5}$, and even the lower concentrations in western and northern Europe contributed substantially (~30%) to the overall estimate of attributable mortality.

Conclusions: Our assessment suggests that air pollution due to $PM_{2.5}$ released from vegetation fires is a notable risk factor for public health in Europe. Moreover, the risk can be expected to increase in the future as the climate change proceeds. This should be taken into consideration when evaluating the overall health and socio-economic impacts of the fires.

Introduction

Vegetation fires, which include wildfires, prescribed forest fires, and open-field burnings related to agricultural practices, release large quantities of combustion-originated air pollutants (Naeher et al. 2007). Of these, particulate matter, and especially fine particles ($PM_{2.5}$, particles with aerodynamic diameter <2.5 μm), are considered most harmful to public health. $PM_{2.5}$ consists of a complex mixture of aerosols, part of which can remain suspended in the atmospheric surface layer for up to a week. It infiltrates efficiently into buildings and enters the lower respiratory tract when inhaled. Numerous epidemiological studies have shown exposure to ambient $PM_{2.5}$ to be associated with respiratory and cardiovascular morbidity and mortality (Pope and Dockery 2006).

Vegetation fires can episodically increase local and regional concentrations of airborne particles manyfold, even by orders of magnitude (Heil and Goldammer 2001; Liu et al. 2015; van Donkelaar et al. 2011). Daily averaged $PM_{2.5}$ concentrations near fire-impacted areas may reach several hundreds of micrograms per cubic meter, and pollution episodes can last from few days to weeks. For comparison, the World Health Organization (WHO) health-based guideline value for daily average $PM_{2.5}$ concentration is 25 $\mu g/m^3$ (WHO 2006). However, the deterioration of air quality is not locally or even regionally limited. If the meteorological conditions are favourable, long-range transport of the fire-originated $PM_{2.5}$ can result in significant increases in short-term exposure levels hundreds or even thousands of kilometres away from the fire-impacted area (Niemi et al. 2009; Sapkota et al. 2005).

Globally, $PM_{2.5}$ exposure from vegetation fires has been estimated to result in over 300,000 premature deaths annually (Johnston et al. 2012). Nearly 80% of these deaths occur in sub-

Saharan Africa and Southeast Asia. This is because the majority of the fire emissions originate from savannas and tropical forests (van der Werf et al. 2010), causing recurrent air pollution episodes in these densely populated regions. However, vegetation-fire originated air pollution has also been suggested to cause substantial public health impacts in developed countries (Hänninen et al. 2009; Kochi et al. 2012; Moeltner et al. 2013).

In Europe, the southernmost countries are heavily impacted by vegetation fires. Between 2000 and 2013, overall 170 000 to 740 000 hectares of land were burned annually by uncontrolled forest, bush, and grassland fires in Portugal, Spain, Italy, Greece, and southern France (EFFIS 2015). Air quality in Europe is also widely affected by fires in eastern European countries and western Russia (Niemi et al. 2009; Witham and Manning 2007), where the common practice of using open-field fires in cropland management is an important source of emissions (Koronzi et al. 2006; van der Werf et al. 2010). In the Black Sea region, agricultural burnings dominate vegetation-fire emissions (van der Werf et al. 2010). However, knowledge on the public health significance of air pollution from vegetation fires in Europe is very limited. This study aims to bridge this information gap by providing quantitative estimates for premature mortality among the general population caused by short-term exposures to the fire-originated $PM_{2.5}$ in different European regions.

Materials and Methods

Emissions and atmospheric transport of vegetation-fire originated $PM_{2.5}$

$PM_{2.5}$ emissions from vegetation fires for the years 2005 and 2008 were computed using the Integrated Monitoring and Modelling System for Wildland Fires (IS4FIRES) (FMI 2016a; Sofiev et al. 2009). The system utilizes the Fire Radiative Power (FRP) (Kaufman et al. 1998) observations of the Moderate-resolution Imaging Spectroradiometer (MODIS) instruments onboard the Aqua and Terra research satellites of the National Aeronautics and Space Administration (NASA) of the USA. FRP is assumed proportional to the biomass burning rate, which is converted to $PM_{2.5}$ emission using land-use dependent empirical emission factors of IS4FIRESv2 (Soares et al. 2015). The Global Land Cover Characterization (GLCC) land-use inventory (Loveland et al. 2000), combined to seven vegetation classes described in Akagi et al. (2011), was used to describe the spatial distribution of different land covers.

Atmospheric transport of the vegetation-fire originated $PM_{2.5}$ was modelled using the chemical transport model The System for Integrated modeLling of Atmospheric coMposition (SILAM) (FMI 2016b; Sofiev et al. 2015). The computations were based on meteorological data (temperature, pressure, wind, humidity, precipitation, cloud cover, and solar radiation) from operational forecasts of the European Centre for Medium-Range Weather Forecasts (ECMWF 2016).

The emission and atmospheric transport computations covered the whole Europe (35°-70°N, 15°W-35°E, see Figure 1) with spatial resolution of $0.3^{\circ}\times0.2^{\circ}$, temporal resolution of 15 minutes and vertical grid consisting of eight unevenly spaced layers stacked up to a height of ~8km. Plume rise was estimated for every fire at every model time step by the algorithm of Sofiev et al. (2012).

To match with data for population distribution, the results of the fire-originated $PM_{2.5}$ simulations – maps of aerosol concentrations – were interpolated to the EMEP standard grid (spatial resolution 50×50 km^2, EMEP 2016).

The years 2005 and 2008 were selected for the analysis because they coincide with relevant datasets available from other projects. In particular, an evaluation of the SILAM transport model performance is available for the year 2005 (Prank et al. 2016), and detailed calibration of the IS4FIRES fire emission data is available for the year 2008 (Soares et al. 2015).

Spatial distribution of population

To assess the number and spatial distribution of the exposed population, we used a population dataset developed in the EU-funded project INTARESE (Briggs 2008). The dataset provides spatially distributed, age- and gender-stratified data for the current and future European population (EU-27, Iceland, Norway, and Switzerland) in the EMEP standard grid (50×50 km^2). In the current assessment, we used gridded estimates for total population in 2010, because it was the nearest available year regarding the years for which air pollution from vegetation fires was modelled (2005 and 2008).

The population dataset and description of its development are available in the Integrated Environmental Health Impact Assessment System (IEHIAS 2016a). Briefly, the dataset was developed on the basis of i) census data from 23 European countries stratified by age and gender and available on the European Local Administrative Unit (LAU) level 2 (municipalities or equivalent units) (IEHIAS 2016b), ii) the United Nations (UN) population data stratified by age and gender (UN 2016), and iii) the Gridded World Population (GWP) data on the spatial distribution of the population (SEDAC 2016). Spatial distribution of the population (age- and gender-stratified) in Europe was determined for the year 2000. This was done by intersecting the census data (in 5-year age-groups and stratified by gender) for LAU 2 regions with EMEP grid cells. If country census data were not available for 5-year age-groups, the population was allocated to 5-year age-groups based on the age distribution of the country population in the UN data. For countries without census data, spatial distribution of the population was based on the age- and gender-stratified UN country population estimates that were area-weighted based on the GWP data. Finally, population growth rates from the UN data (for each country and population subgroup separately) were used to project the 2000 data to the future years.

Mortality impact analysis

Within all countries included in our mortality assessment, only 4-5% of the modelled vegetation-fire originated daily average grid-cell $PM_{2.5}$ concentrations in 2005 and 2008 were above 1 μg/m^3 and less than 1% were above 5 μg/m^3 (see Supplemental Material, Tables S1 and S2). Therefore, exposure to moderate or high levels of vegetation-fire smoke is sporadic, and mortality due to the smoke exposure was evaluated on the basis of acute mortality risk related to short-term increases in $PM_{2.5}$ concentrations. First, the relative mortality risk due to the fire-originated $PM_{2.5}$ in each grid-cell and day of the year was calculated as

$$RR' = \exp(\ln(RR) / 10 \times C), \quad [1]$$

where RR is the relative-risk exposure-response function for daily $PM_{2.5}$ exposure and non-accidental mortality, and C is the modelled daily average concentration of the fire-originated $PM_{2.5}$ (μg/m^3) in the grid-cell. For the exposure-response function, we assumed an RR of 1.0098 per 10 μg/m^3 (95% confidence interval: 1.0075, 1.0122), i.e. 0.98% increase in the risk of non-accidental mortality per each 10 μg/m^3 increment in the source-specific $PM_{2.5}$ concentration. The estimate is based on an epidemiological study on the mortality effects of short-term urban $PM_{2.5}$ exposures in 112 US cities (Zanobetti and Schwartz 2009).

Next, the population attributable fraction (PAF), i.e. the fraction of population mortality attributable to the fire-originated $PM_{2.5}$, was calculated for each grid-cell and day as

$$PAF = (RR' - 1) / RR', \qquad [2]$$

Finally, the number of daily deaths attributable to the fire-originated $PM_{2.5}$ in each grid-cell was calculated as

$$\text{Attributable deaths} = P \times MR \times PAF, \qquad [3]$$

where P is the country-specific population in the grid-cell, and MR is the country-specific daily background mortality risk. For each country, the daily background risk for non-accidental mortality in 2005 and 2008 was estimated on the basis of the yearly mortality statistics from the World Health Organization (WHO) Mortality Database (WHO 2013a). If country data was not available for these years, data for the nearest possible year was used. The daily average mortality risk was defined by dividing the annual mortality risk by the number of days in the year (365 in 2005, 366 in 2008). Finally, the daily attributable deaths were summed over all days of the year and country- or region-specific grid-cells.

We assumed a linear exposure-response function at all vegetation-fire originated $PM_{2.5}$ concentration levels. However, the applied exposure-response function is valid for short-term urban levels of $PM_{2.5}$ commonly encountered in developed countries (daily concentrations generally well below 100 $\mu g/m^3$). Because there were some higher values among the modelled fire-originated daily $PM_{2.5}$ concentrations, and because cardiovascular mortality effects of long-term exposures have been suggested to flatten out at high PM levels (Pope et al. 2011), we wanted to test the sensitivity of the assessment outcome to the possible overestimation of the mortality effect at high vegetation-fire originated $PM_{2.5}$ levels. To achieve this, we made an additional analysis, in which the mortality impacts were calculated by fixing the modelled daily $PM_{2.5}$ concentrations exceeding 100 μg/m^3 to be equal to 100 μg/m^3.

The mortality impacts associated with vegetation-fire originated $PM_{2.5}$ were assessed for altogether 27 European countries, for which all required input data was available. The countries were further classified into northern, eastern, western, and southern European regions (see Table 1).

Results

Emissions and atmospheric transport of vegetation-fire originated $PM_{2.5}$

The large-scale distribution of the modelled vegetation-fire emissions in 2005 and 2008 were similar: the fires were intensive mainly in northern Portugal and Spain, southern Italy, the Balkans, the Black Sea area, the Kaliningrad area and other parts of western Russia (Figure 1A and B, and Supplemental Material, Table S3 for country-specific emission estimates). The main difference between the two years was in the strength of the fires in the southern and eastern regions, which can at least partly be explained by the differences in the fire-season (April-October) temperatures and precipitation between 2005 and 2008 in these regions (Supplemental Material, Figure S1). Year 2005 was hot and dry in the Iberian Peninsula, leading to a large number of vegetation fires, whereas the cooler and wetter conditions in 2008 led to relatively few fires. In contrast, year 2008 was hotter and dryer than average in the Balkan region and southern Italy, resulting in more extensive fires compared to 2005.

Model-based estimates of vegetation-fire originated $PM_{2.5}$ concentrations (Figure 1C and D) follow the spatial distributions for the vegetation-fire emissions (Figure 1A and B), but the smoke affected wider regions than the fire areas. In 2005, the highest concentrations were located in northern Portugal and Spain, whereas in 2008 the pollution was highest in countries bordering the Black Sea. In northern Europe, winds during the fire season (April-October) were stronger and more frequently northerly in 2005 compared to 2008 (Supplemental Material, Figure S2). As a consequence, long-range transported vegetation-fire smoke reached higher latitudes in 2005 than 2008. However, long-term mean statistics of wind patterns do not adequately characterize yearly variations in population smoke exposure, which depends strongly on the short-term wind directions and other conditions affecting smoke aerosol transport during the fire events.

The WHO health-based guideline value for daily $PM_{2.5}$ (25 $\mu g/m^3$) was exceeded solely due to the vegetation-fire originated smoke only in few places and days (Figure 1E and F). However, in Portugal the exceedance lasted for about three weeks in 2005.

Population-weighted annual average concentrations of the vegetation-fire originated $PM_{2.5}$ in different countries ranged from 0.02 to 2.8 $\mu g/m^3$ in 2005 and 0.02 to 1.1 $\mu g/m^3$ in 2008 (Table 1). Between 2005 and 2008, there were substantial country-level variations in exposure, particularly within the southern and eastern regions of Europe. However, in both 2005 and 2008 the regional-level population-weighted concentrations were clearly highest in the South and the East and lowest in the North.

Mortality impact

In the 27 countries assessed, we estimated that 1483 and 1080 premature deaths were attributable to the vegetation-fire originated $PM_{2.5}$ in 2005 and 2008, respectively, assuming RR = 1.0098 for a 10 μg/m^3 increase in $PM_{2.5}$ (Table 2). Ranges of uncertainty estimated using the lower and upper 95% confidence interval bounds for the exposure-response function from Zanobetti and Schwartz (2009) (RR = 1.0075 and 1.0122, respectively) were 1139–1839 for attributable premature deaths in 2005, and 828–1342 in 2008. In absolute terms, the estimated number of deaths attributable to the vegetation-fire originated $PM_{2.5}$ was comparable in the southern, eastern, and western regions of Europe. In relative terms (per 100 000 inhabitants), the attributable mortality was clearly highest in the southern and eastern regions. In the South and the East the mortality impacts peaked in summer, whereas in the North and the West the monthly variation was less pronounced (Figure 2).

Overall, our estimates suggest that the majority (70-80%) of the premature deaths attributable to the vegetation-fire originated $PM_{2.5}$ in 2005 and 2008 were caused by relatively low to moderate increases in daily concentrations (≤15 μg/m^3). This was particularly seen in the western and northern regions, where $PM_{2.5}$ increases of ≤2 μg/m^3 and ≤15 μg/m^3 were estimated to have caused 60-80% and ~99% of the premature deaths, respectively (Table 3).

The sensitivity analysis regarding the possible overestimation of the $PM_{2.5}$ mortality effect at high exposure levels showed a negligible effect on the assessment outcome (data not shown):

limiting the modelled vegetation-fire originated $PM_{2.5}$ concentrations above 100 μg/m^3 to 100 μg/m^3 reduced the total mortality estimate in Europe for 2005 by 1.6% and the estimate for 2008 by 0.01%.

Discussion

Wildfires can be catastrophic events leading to immediate life losses and resulting in damage costs in the order of billions of euros (San-Miguel-Ayanz et al. 2013). While they cause a lot of public concern, their far-reaching effects on air quality are often ignored. Our assessment suggests that fine particles emitted from vegetation fires may affect health widely in Europe, causing tens to hundreds of premature deaths in many countries annually. Hence, our estimates indicate that the overall mortality attributable to the fires is far higher and more widespread than the immediate fatalities reported from the fire-impacted areas.

In 2005 and 2008, the modelled exposure to the vegetation fire-originated $PM_{2.5}$ and the resulting mortality effect estimates were, on a regional level, several times higher in the fire-prone southern and eastern European countries compared to the western and northern countries. In the South and the East, the estimated pollution and mortality impacts clearly peaked in July-August, which is the strongest fire season for both wildfires and agricultural-waste burnings in these areas (Korontzi et al. 2006; Magi et al. 2012). However, our findings suggest that the western and northern European countries were also affected, to a large extent due to long-range transport of the fire smoke. In the West and the North, estimated annual fire-originated $PM_{2.5}$ concentrations were, in general, clearly lower than those in the South and the East, and more evenly distributed throughout the spring, summer and autumn months. However, exposures to these lower source-specific $PM_{2.5}$ levels accounted for a substantial proportion of the estimated overall mortality impact of the vegetation-fire emissions in Europe, because large numbers of people were exposed over extensive areas, especially in western Europe.

In the 27 countries overall, we estimated that daily average fire-originated $PM_{2.5}$ concentrations of 15 $\mu g/m^3$ or less, which are low to moderate in comparison to typical urban $PM_{2.5}$ concentrations in Europe, accounted for more than 70% of the premature deaths attributed to the $PM_{2.5}$ from vegetation fires. In the northern and western regions, we estimated that 60-80% of the attributable deaths resulted from increments <2 $\mu g/m^3$, which are small compared to normal daily variation in $PM_{2.5}$ in European cities (up to tens of $\mu g/m^3$). However, our estimates also demonstrate the potential extent of health impacts arising from severe pollution episodes in large-scale fire events, such as the one in 2005 in north-west Portugal (San-Miguel-Ayanz et al. 2013). During this type of event, $PM_{2.5}$ levels in the nearby areas can increase manyfold, leading to severe health effects over a period of several weeks. Furthermore, in areas with relatively low long-term levels of air pollution, increases in daily $PM_{2.5}$ classified here as moderate can, from a local perspective, mean substantial worsening of the air quality.

Although our assessment suggests widespread health effects of vegetation-fire originated $PM_{2.5}$ in Europe, our exposure estimates did not account for fire $PM_{2.5}$ transported to Europe from areas outside the emission grid used in our analysis (e.g. from Central Asia and Central Russia). More importantly, our mortality estimates did not include Ukraine, Belarus, and south-western European Russia, which are hot spots for vegetation-fire emissions. Furthermore, health effects of fire-originated $PM_{2.5}$ are not limited to increases in mortality, but include a wide range of less severe health outcomes, such as worsening of respiratory and cardiovascular diseases (Pope and

Dockery 2006). In addition to $PM_{2.5}$, fire smoke also contains other pollutants harmful to health, such as coarse thoracic particles (size-range 2.5-10 μm), nitrogen dioxide, ozone, and a large variety of gaseous hydrocarbons (Naeher et al. 2007). Adverse health effects associated with the factors listed above were not considered in the present assessment.

Assessing only two years is, of course, a major limitation for drawing general conclusions on the health effects of vegetation-fire originated $PM_{2.5}$ in Europe. It raises the question whether our exposure and mortality estimates represent the low- or the high-end of the inter-annual variation in the impacts. Due to weather conditions, vegetation characteristics and human factors (Flannigan et al. 2009), there are considerable yearly differences in fire activity, which was also manifested in our study. According to data from the European Forest Fire Information System, the area burned in the Iberian Peninsula in 2005 was the second largest and in 2008 the smallest recorded from 2000 to 2013 (EFFIS 2015). The difference in the extent and severity of the fires between 2005 and 2008 was particularly striking in Portugal. Hence, the mortality estimates for the Iberian Peninsula, and especially Portugal, likely indicate the potential range of annual impacts in the 2000's.

Based on the IS4FIRES inventory, for the whole of Europe the overall emissions of vegetation-fire originated PM in 2005 and 2008 were not drastically different compared to other years from 2000 to 2013 (see Supplemental Material, Figure S3). This suggests that, apart from the Iberian Peninsula, our mortality estimates are unlikely to represent years with uncommonly high or low overall impacts in Europe. This is also supported by Giglio et al. (2013), who have provided burned-area estimates for different world regions in the 2000's based on the fourth-generation Global Fire Emissions Database (GFED4) inventory. However, exposures and health impacts of air pollution from vegetation-fires are not only determined by the area burned or the total emissions, but also depend on the proximity of fires to densely populated areas and the prevailing emission transport conditions during the fires. Therefore, it remains unclear to what extent the regional mortality impacts in 2005 and 2008 can be generalised to other years.

Validity of any health impact assessment on vegetation-fire originated air pollution depends on the quality of the emission and atmospheric transport modelling. In the IS4FIRES emission estimates used in the current assessment, there are uncertainties due to (i) the strong diurnal variations in the fire intensity that are not resolved by the MODIS FRP observations, (ii) difficulties in observing small fires, which are quite frequent in Europe (leading to about 10% loss in emissions), and (iii) very limited information on burning characteristics and, consequently, emission factors for individual fires (Soares et al. 2015). Within the IS4FIRES, these (potentially large) uncertainties are constrained during the system calibration step, which adjusts the emission factors based on comparison of MODIS aerosol optical depth (AOD) observations of atmospheric PM and SILAM simulations of the fire-smoke distribution. In the AOD observations, it is not possible to distinguish the fire-originated PM from that originating from other sources. Therefore, the IS4FIRES system calibration is based on episodes with strong domination of fire-induced pollution. However, such episodes are not common in Europe, where the fire contribution to total PM is usually relatively small. This increases the uncertainty in the European fire emissions and makes it difficult to assess their accuracy.

In regard to the atmospheric transport modelling, the main uncertainties include i) vertical distribution of the emissions, ii) particle properties, and iii) formation of secondary particles when fire-originated gaseous compounds released to the atmosphere participate in chemical reactions. However, calibration of the IS4FIRES vegetation-fire emission factors is based on observed AOD with the majority of the fire plumes being at least several hours old. As a result, the majority of the secondary particle formation would have already occurred and is, therefore, included in the modelled fire-originated $PM_{2.5}$ concentrations. Overall, when SILAM simulations of atmospheric $PM_{2.5}$ total concentrations are compared with daily air quality observations from the EMEP observational network, SILAM performs reasonably well (Prank et al. 2016). Similar to other regional transport models, SILAM tends to underestimate the observed PM levels. This is mainly because some PM components, such as wind-blown dust, secondary organic aerosol and aerosol-bound water, are omitted from the simulations. However, when compared to three other transport models, SILAM showed the smallest underestimation for total $PM_{2.5}$ (~25%, Prank et al. 2016).

Nevertheless, our modelled concentrations of vegetation-fire originated $PM_{2.5}$ are likely to overestimate the influence of strong fires. This is based on the notion that when SILAM simulations of total $PM_{2.5}$ are compared with $PM_{2.5}$ measurements at a monitoring station affected by intensive fire episodes in summer months, the underestimation expected in the modelled total $PM_{2.5}$ concentrations due to the PM components omitted from the simulations is not evident (Supplemental Material, Figure S4A). Because the omitted components (wind-blown dust and secondary organic aerosol) are abundant in summertime, a negative bias between the modelled and measured $PM_{2.5}$ is expected to remain also during summer. This negative bias is, in fact, evident in a monitoring station not influenced by vegetation fires (Supplemental Material, Figure S4B). Thus, it is likely that overestimation of $PM_{2.5}$ from strong vegetation fires partly masks the underestimation due to the PM components lacking from the simulations.

On the other hand, due to the difficulties in detecting small vegetation fires (Soares et al. 2015), $PM_{2.5}$ emissions and exposure from small fires are probably underestimated in our assessment. While majority of wildfires are started by people and, hence, occur near populated areas (Ganteaume et al. 2013), fires in inhabited regions are usually small in size compared to remote areas (Archibald et al. 2009; Knorr et al. 2014). This is likely due to the more fragmented landscape, which limits the fire spread, and the more efficient fire suppression. However, because of the shorter distance to the people, and because smoke plumes of small fires stay near the ground, the impact of small fires on population exposure can be substantial.

The accuracy of the mortality estimates also depends on whether the exposure-response function for urban $PM_{2.5}$ is valid for estimating impacts of vegetation-fire $PM_{2.5}$. Although the adverse effects of urban $PM_{2.5}$ on respiratory and cardiovascular morbidity and mortality have been clearly demonstrated (Pope and Dockery 2006), epidemiological evidence on the effects of $PM_{2.5}$ from biomass burning is scarcer. However, the current consensus based on the physical and chemical properties of the particles, and on toxicological and epidemiological studies, is that PM released from biomass burning should not be considered less harmful to human health than ambient air PM in general (Naeher et al. 2007; WHO 2013b). Epidemiological studies have demonstrated associations between exposure to wildfire smoke and respiratory health effects, and the evidence on cardiovascular effects has strengthened (Faustini et al. 2015; Liu et al. 2015; WHO 2013b; Youssouf et al. 2014). Associations with increased mortality have also been reported (Analitis et al. 2012; Faustini et al. 2015; Johnston et al. 2011; Sastry 2002), but few studies have attempted to quantify the size of the mortality effect per unit increase in vegetation-fire PM exposure.

Adverse health effects of air pollution may also vary between populations because of differences in, for example, exposure to outdoor air pollutants, population age structure, and prevalence of diseases. Therefore, the exposure-response function used in our analysis, which was estimated for the US population (Zanobetti and Schwartz 2009), may not be valid for estimating mortality impacts in different regions of Europe. Evidence on short-term mortality effects of urban $PM_{2.5}$ in Europe is less comprehensive compared to the US. However, a meta-analysis on the existing European single and multi-city studies suggests that the mortality effect of $PM_{2.5}$ is similar in Europe (RR 1.0123 per 10 $\mu g/m^3$) (Héroux et al. 2015; WHO 2013c) and in the US (RR 1.0098 per 10 $\mu g/m^3$) (Zanobetti and Schwartz 2009).

Because of the climate change, vegetation fires are a growing concern in the future (Flannigan et al. 2009). In Europe, the risk of wildfires has been projected to increase in most regions. Recent estimates for the potential increase in the overall area burned vary from 40 to 200% by the end of the 21st century compared to the present situation (Khabarov et al. 2016; Migliavacca et al. 2013). The absolute increase in burned area is expected to be high especially in the southern and eastern Europe. However, in relative terms the impacts may be notable also in the central and northern Europe. Moreover, as fires often coincide with heat waves, interaction between air pollution and heat exposure on cardiovascular and respiratory health can increase health impacts considerably (Shaposhnikov et al. 2014). This is important especially during severe heat waves, which are predicted to become more common as the climate change proceeds (IPCC 2013).

Because fire is an inherent process in forest and grassland ecosystems in their natural state, wildfires and their emissions can be prevented only to a certain extent. However, vegetation management and other fire prevention and suppression practices are necessary near populated areas to reduce the risk of catastrophic events (Moreira et al. 2011; San-Miguel-Ayanz et al. 2013). In addition, emissions from agricultural-waste burning could be reduced by more effective regulations on open-field fires, particularly in the eastern European countries. Public health can also be protected by providing timely warnings and advice on how to reduce health risks during air pollution episodes, for example by staying indoors and keeping windows closed, avoiding physical activities in polluted outdoor environments, and using room air cleaners to improve indoor air quality (Elliott 2014). Information and assistance should be targeted especially towards population groups most vulnerable to air pollution, namely the elderly, the young children, and those with a pre-existing respiratory or cardiovascular disease.

Conclusions

Our findings suggest that exposure to $PM_{2.5}$ originated from vegetation fires causes tens to hundreds of premature deaths each year in many European countries. The estimated impacts are highest in fire-prone regions in southern and eastern Europe, but other regions are also affected. Adverse effects of the fire-originated air pollution on public health should be taken into consideration when evaluating the overall health and socio-economic consequences of vegetation fires, which are expected to increase as the climate change proceeds.

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Table 1. Population-weighted annual average concentration[a] (μg/m^3) of vegetation-fire originated $PM_{2.5}$.

Region, country	2005	2008
Northern Europe	***0.07***	***0.04***
Denmark	0.10	0.05
Finland	0.06	0.05
Norway	0.04	0.02
Sweden	0.08	0.04
Eastern Europe	***0.39***	***0.45***
Bulgaria	0.67	1.11
Czech Republic	0.26	0.15
Estonia	0.09	0.11
Hungary	0.48	0.39
Latvia	0.12	0.13
Lithuania	0.25	0.17
Poland	0.25	0.16
Romania	0.66	1.08
Slovenia	0.21	0.15
Slovakia	0.39	0.26
Western Europe	***0.19***	***0.12***
Austria	0.28	0.23
Belgium	0.33	0.20
France	0.17	0.10
Germany	0.24	0.16
Ireland	0.02	0.03
Luxembourg	0.35	0.13
Netherlands	0.27	0.18
Switzerland	0.08	0.05
United Kingdom	0.09	0.08
Southern Europe	***0.57***	***0.26***
Greece	0.41	0.79
Italy	0.25	0.33
Portugal	2.77	0.06
Spain	0.52	0.08
All regions	**0.32**	**0.22**

[a]Estimated based on emissions from the Integrated Monitoring and Modelling System for Wildland Fires (IS4FIRES, FMI 2016a), chemical transport model the System for Integrated modeLling of Atmospheric coMposition (SILAM, FMI 2016b), and INTARESE data on population distribution in Europe (IEHIAS 2016a).

Table 2. Central estimate and uncertainty range for premature deaths[a] (total number and death-rate per 100 000 inhabitants) attributable to vegetation-fire originated $PM_{2.5}$.

	Attributable deaths, total		Attributable deaths per 100 000	
Region, country	**2005**	**2008**	**2005**	**2008**
Northern Europe	***17 (13, 21)***	***9 (7, 12)***	***0.07 (0.05, 0.08)***	***0.04 (0.03, 0.05)***
Denmark	5 (4, 6)	3 (2, 3)	0.09 (0.07, 0.11)	0.05 (0.04, 0.06)
Finland	3 (2, 3)	2 (2, 3)	0.05 (0.04, 0.06)	0.04 (0.03, 0.05)
Norway	2 (1, 2)	1 (1, 1)	0.04 (0.03, 0.05)	0.02 (0.01, 0.02)
Sweden	7 (5, 9)	4 (3, 5)	0.08 (0.06, 0.09)	0.04 (0.03, 0.05)
Eastern Europe	***428 (328, 531)***	***499 (383, 620)***	***0.42 (0.32, 0.52)***	***0.49 (0.38, 0.61)***
Bulgaria	68 (52, 85)	112 (86, 139)	0.91 (0.70, 1.13)	1.50 (1.15, 1.86)
Czech Republic	26 (20, 32)	15 (11, 18)	0.25 (0.19, 0.31)	0.14 (0.11, 0.17)
Estonia	1 (1, 2)	2 (1, 2)	0.10 (0.08, 0.13)	0.12 (0.09, 0.15)
Hungary	58 (45, 72)	46 (35, 57)	0.59 (0.45, 0.73)	0.46 (0.35, 0.57)
Latvia	3 (3, 4)	4 (3, 4)	0.15 (0.12, 0.19)	0.16 (0.12, 0.20)
Lithuania	8 (7, 10)	6 (5, 8)	0.26 (0.20, 0.32)	0.19 (0.15, 0.24)
Poland	84 (64, 104)	54 (42, 67)	0.22 (0.17, 0.27)	0.14 (0.11, 0.18)
Romania	156 (119, 193)	246 (189, 306)	0.73 (0.56, 0.91)	1.16 (0.89, 1.44)
Slovenia	4 (3, 4)	2 (2, 3)	0.18 (0.13, 0.22)	0.12 (0.09, 0.15)
Slovakia	19 (15, 24)	13 (10, 16)	0.35 (0.27, 0.44)	0.23 (0.18, 0.29)
Western Europe	***415 (318, 515)***	***278 (213, 345)***	***0.16 (0.12, 0.20)***	***0.11 (0.08, 0.14)***
Austria	20 (15, 24)	16 (12, 20)	0.23 (0.18, 0.29)	0.19 (0.14, 0.23)
Belgium	32 (25, 40)	19 (14, 23)	0.30 (0.23, 0.37)	0.17 (0.13, 0.22)
France	83 (64, 103)	48 (36, 59)	0.13 (0.10, 0.17)	0.08 (0.06, 0.10)
Germany	186 (142, 231)	127 (97, 158)	0.22 (0.17, 0.28)	0.15 (0.12, 0.19)
Ireland	1 (1, 1)	1 (1, 1)	0.01 (0.01, 0.02)	0.02 (0.01, 0.02)
Luxembourg	1 (1, 2)	0 (0, 1)	0.25 (0.19, 0.31)	0.09 (0.07, 0.11)
Netherlands	35 (27, 43)	23 (18, 29)	0.21 (0.16, 0.26)	0.14 (0.11, 0.17)
Switzerland	4 (3, 5)	3 (2, 4)	0.06 (0.04, 0.07)	0.04 (0.03, 0.05)
United Kingdom	52 (40, 65)	42 (32, 52)	0.08 (0.06, 0.11)	0.07 (0.05, 0.08)
Southern Europe	***624 (480, 772)***	***294 (225, 365)***	***0.50 (0.38, 0.61)***	***0.23 (0.18, 0.29)***
Greece	40 (31, 50)	80 (62, 100)	0.36 (0.27, 0.45)	0.72 (0.55, 0.89)
Italy	133 (102, 166)	182 (139, 226)	0.22 (0.17, 0.28)	0.30 (0.23, 0.38)
Portugal	260 (201, 321)	5 (4, 7)	2.51 (1.94, 3.10)	0.05 (0.04, 0.06)
Spain	190 (146, 235)	26 (20, 33)	0.43 (0.33, 0.53)	0.06 (0.05, 0.07)
All regions	***1483 (1139, 1839)***	***1080 (828, 1342)***	***0.29 (0.22, 0.36)***	***0.21 (0.16, 0.26)***

[a]Estimated based on a relative mortality risk of 1.0098 per 10 µg $PM_{2.5}/m^3$ (Zanobetti and Schwartz 2009), INTARESE data on population distribution in Europe (IEHIAS 2016a), and background mortality data from WHO Mortality Database (WHO 2013a). Uncertainty range is based on the upper and lower bounds of the 95% CI of the exposure-response function (1.0075, 1.0122, Zanobetti and Schwartz 2009).

Table 3. Relative frequency of modelled daily average grid-cell concentrations[a] of vegetation-fire originated $PM_{2.5}$, and premature deaths[b] attributable to these concentrations.

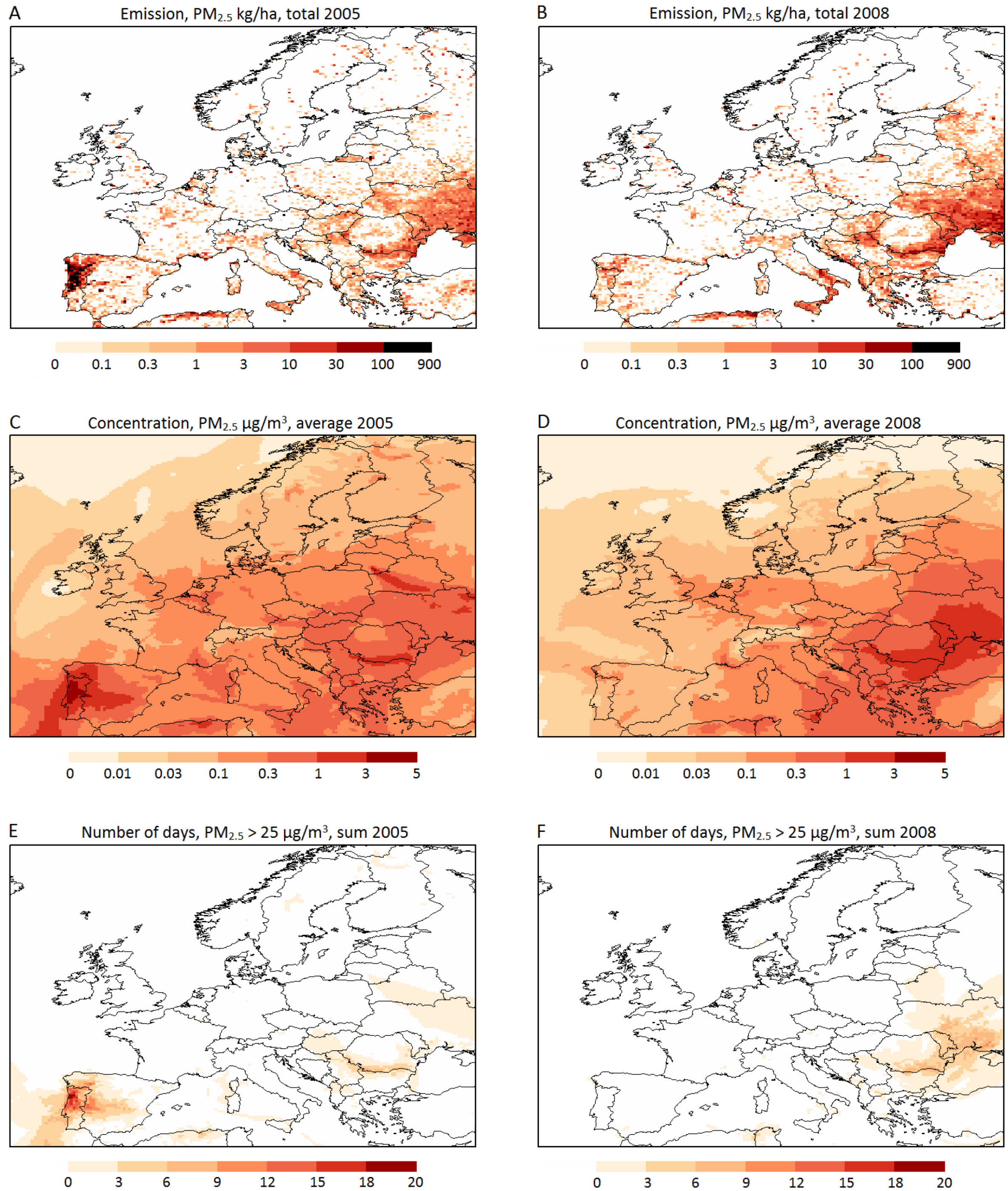
	PM2.5 <0.5 µg/m³		$PM_{2.5}$ 0.5-2 µg/m³		$PM_{2.5}$ 2-15 µg/m³		$PM_{2.5}$ >15 µg/m³	
Year, region	**Relative frequency**	**Attributable deaths**	**Relative frequency**	**Attributable deaths**	**Relative frequency**	**Attributable deaths**	**Relative frequency**	**Attributable deaths**
2005								
Northern Europe	97.0%	5	2.7%	8	0.3%	3	0.01%	0.2
Eastern Europe	85.7%	49	10.3%	119	3.6%	160	0.3%	100
Western Europe	92.6%	90	6.1%	166	1.3%	155	0.01%	4
Southern Europe	88.1%	54	7.8%	82	3.5%	167	0.7%	320
All regions	90.8%	198	6.7%	375	2.2%	485	0.3%	424
2008								
Northern Europe	98.8%	4	1.0%	3	0.2%	2	0.001%	0.1
Eastern Europe	87.8%	54	7.7%	87	3.9%	202	0.6%	157
Western Europe	95.2%	80	4.1%	119	0.7%	77	0.004%	1
Southern Europe	89.4%	46	7.0%	84	3.5%	137	0.1%	26
All regions	92.7%	185	5.0%	294	2.1%	418	0.2%	184

[a]Estimated based on emissions from the Integrated Monitoring System for Wildland Fires (IS4FIRES, FMI 2016a) and chemical transport model the System for Integrated modeLling of Atmospheric coMposition (SILAM, FMI 2016b).
[b]Estimated based on a relative mortality risk of 1.0098 per 10 µg $PM_{2.5}/m^3$ (Zanobetti and Schwartz 2009), INTARESE data on population distribution in Europe (IEHIAS 2016a), and background mortality data from the WHO Mortality Database (WHO 2013a).

Figure 1. Modelled emissions and atmospheric transport of vegetation-fire originated $PM_{2.5}$ for 2005 and 2008. Panels a & b) annual emissions (kg/ha), c & d) annual average concentrations ($\mu g/m^3$), and e & f) the number of days when the daily average concentration of fire-originated $PM_{2.5}$ exceeded the WHO health-based guideline value of 25 $\mu g/m^3$. Left panels represent year 2005, right ones year 2008. Emissions were modelled using the Integrated Monitoring System for Wildland Fires (IS4FIRES, FMI 2016a). Atmospheric transport was modelled using the System for Integrated modeLling of Atmospheric coMposition (SILAM, FMI 2016b).

Figure 2. Monthly distribution of premature deaths attributable to vegetation-fire originated $PM_{2.5}$ in different regions of Europe. Numbers represent months beginning from January. Attributable mortality was estimated based on a relative risk of 1.0098 per 10 $\mu g\ PM_{2.5}/m^3$ (Zanobetti and Schwartz 2009), INTARESE data on population distribution in Europe (IEHIAS 2016a), and background mortality data from the WHO Mortality Database (WHO 2013a).

Figure 1.


A
Emission, PM2.5 kg/ha, total 2005
0 0.1 0.3 1 3 10 30 100 900
B
Emission, PM2.5 kg/ha, total 2008
0 0.1 0.3 1 3 10 30 100 900
C
Concentration, PM2.5 µg/m3, average 2005
0 0.01 0.03 0.1 0.3 1 3 5
D
Concentration, PM2.5 µg/m3, average 2008
0 0.01 0.03 0.1 0.3 1 3 5
E
Number of days, PM2.5 > 25 µg/m3, sum 2005
0 3 6 9 12 15 18 20
F
Number of days, PM2.5 > 25 µg/m3, sum 2008
0 3 6 9 12 15 18 20

Environ Health Perspect DOI: 10.1289/EHP194
Advance Publication: Not Copyedited

Figure 2.